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14. ABSTRACT
This project aims to develop a framework that blends constructs from system theory and theory of networks to address problems pertaining to security and robustness of networked dynamic systems. Such networks have the additional layer of having "dynamics" overlapping the interconnection geometry— and as such, the necessary formalisms for examining them and useful methodologies for their analysis and synthesis, are only beginning to take shape. Yet as the next generation Air Force systems more and more consist of dynamics entities interacting over complex networks, the study of the security and robustness of networked systems from a control and system theoretic point of view becomes of paramount importance.

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1 Objectives

This project aims to develop a framework that blends constructs from system theory and theory of networks to address problems pertaining to security and robustness of networked dynamic systems. Such networks have the additional layer of having "dynamics" overlapping the interconnection geometry— and as such, the necessary formalisms for examining them and useful methodologies for their analysis and synthesis, are only beginning to take shape. Yet as the next generation Air Force systems more and more consist of dynamics entities interacting over complex networks, the study of the security and robustness of networked systems from a control and system theoretic point of view becomes of paramount importance.

In line with this observation, the objectives of this research effort is as follows:

1. **Task 1 (Dynamic Network Security):** In this task, we consider means by which a particular coordination scheme for the operation of multiple agents can potentially be manipulated. Specifically, we examine how particular aspects of network topology, pertaining to its symmetry structure- or more formally- its automorphism group, allows for the *control of the entire network* by one or a small number of intruders. Although it is tempting to conjecture that it is sufficient to consider static features of networks for addressing such an inquiry, in this proposal, we argue that system theory plays a significant role in shedding light on issues related to dynamic security of networks.

2. **Task 2 (Observability of Dynamic Networks):** This task, which can conceptually be considered as the dual of the network security problem above, involves examining the following question: under what conditions does the network structure allows for intruding agents at one or a few of the network nodes, "observe" the state of the entire network? This task will shed light on the security of the network from the observation point of view.

3. **Task 3 (Probabilistic Robustness of Networks:)** In this task, we examine the effect of random network connections on the performance of networked dynamic systems. In this avenue, we allow the network- required for the operation of dynamic agents- to have a random character and consider the following sets of questions: (1) what are the benefits of network randomness for the operation of these systems from the security point of view? and (2) what are the performance degradation of a networked system as a function of the reliability of underlying random network? In this task, we aim to identify *performance thresholds* that can qualitatively assess the behavior of the networked agents as a function of the reliability of the network interconnections.

4. **Task 4 (Network Factorization):** This task involves exploring the powerful machinery of graph factorization - in terms of its Cartesian product- which enables assessing the security and performance of systems on large-scale networks in terms of the corresponding attributes on smaller sized-networks, i.e., its factors.

2 Project Accomplishments

As supported by this project, we have made a number of significant contributions in the area of assessing the security and controllability of diffusion-like processes over networks:

- First, we have been able to parameterize the (average) resistance of networks to external influence by use of quadratic measures, that have subsequently been related to network effective resistance and theory of random walks.

- Second, we have also looked at extremal cases for characterizing the vulnerability of such networks.

- Third, using these characterizations, we have then proceeded to use a game-theoretic methodology to propose local protocols for how the network should locally alter its geometry, in order to make itself more resistant to external influence. In this venue, notions such as network Nash equilibria has been introduced and utilized to examine the sub-optimality properties of the resulting network equilibria.

- Assessing the security of random dynamic networks, where the network assumes a random graph realization during each interval, has been another facet of our research. In this direction, we have proposed a formalism by which it can be shown that dynamic random network models are controllable and observable in the stochastic setting, allowing an intruder that can access a *random set* of nodes during a given interval to adversely effect the evolution of the network. The implications of this observation in the context of filtering and observing random graph models and its security implications have also been examined.

- Examining the relation between network controllability and network entropy and ramifications for security of entropic network configurations.

Another accomplishments of the PI during this project was publishing a book on graph theoretic methods for dynamic networks (with M. Egerstedt; see below).

3 Personnel Supported

- Marzieh Nabi (Graduate Student); expected graduation: Summer 2012.

- Airlie Chapman (Graduate Student); expected graduation: Spring 2013.

- Mehran Mesbahi (PI)

4 Publications

4.1 Books

- M. Mesbahi and M. Egerstedt, *Graph Theoretic Methods in Multiagent Networks*, Princeton University Press, 2010 (see http://press.princeton.edu/titles/9230.html).

4.2 Peer-reviewed Journal and Conference Papers

- A. Chapman and M. Mesbahi, Semi-autonomous networks: theory and examples, *IEEE Transactions on Automatic Control* (to appear).

- A. Chapman and M. Mesbahi, Influence models for consensus-type networks, *IEEE Transactions on Automatic Control* (to appear).

- M. Nabi and M. Mesbahi, Network identification via node knockouts, *IEEE Transactions on Automatic Control* (to appear).

- Z. Wu and M. Mesbahi, Symplectic transformation based approach for linear quadratic control with terminal constraints, *SIAM Journal of Control and Optimization*, 50 (2), 652-671, 2012.

- Rajapakse, M. Groudine, and M. Mesbahi, Dynamics and control of state-dependent networks for probing genomic organization, *Proceedings of the National Academy of Sciences*, doi: 10.1073/pnas.1113249108, 2011.

- D. Zelazo and M. Mesbahi, Graph-theoretic analysis and synthesis of relative sensing networks, *IEEE Transactions on Automatic control*, 56 (5): 971-982, 2011.
- D. Zelazo and M. Mesbahi, Edge agreement: graph-theoretic performance bounds and passivity analysis, *IEEE Transactions on Automatic Control,* 56 (3): 544 - 555, 2011.
- D. Zelazo and M. Mesbahi, H_∞ performance and robust topology design of relative sensing networks, *American Control Conference*, 2010.
- A. Das, Y. Hatano, and M. Mesbahi. Agreement over noisy networks, *IET Control Theory and Applications*, 4 (11): 2416 - 2426, 2010.
- A. Chapman and M. Mesbahi, Semi-Autonomous Networks: Network Resilience and Adaptive Trees, *IEEE Conference on Decision and Control*, 2010.
- M. Nabi-Abdolyousefi and M. Mesbahi, Network identification via node knock-out, *IEEE Conference on Decision and Control*, 2010.
- A. Chapman and M. Mesbahi. Stability Analysis of Nonlinear Networks via M-matrix Theory: Beyond Linear Consensus, *American Control Conference*, 2012.
- A. Chapman and M. Mesbahi. Advection on Graphs, *IEEE Conference on Decision and Control*, 2012.
- M. Nabi-Abdolyousefi and M. Mesbahi, System theory over random networks: controllability and optimality properties, *IEEE Conference on Decision and Control*, 2011.
- M. Nabi-Abdolyousefi and M. Mesbahi, Coordinated decentralized estimation over random networks, *American Control Conference*, 2011.

5 Interactions/Transitions

We have made a number of presentations on the research supported by this work during the previous funding period. Examples include,

- Invited/plenary speaker at Georgia Tech, Jet Propulsion Laboratory, UC Santa Barbara, Concordia University, University of Washington
- Conference presentations at IEEE CDC, American Control Conference, and ICRA.

6 Honors/Awards

- Professor of the Year; University of Washington Department of Aeronautics and Astronautics, 2010.
- Featured Speaker, UW College of Engineering Fall Series (Re-engineering Aerospace) 2011 (also on UWTV).